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PRODUCTION OF MUONS FOR FUSION CATALYSIS IN A MAGNETIC MIRROR CONFIGURATION*

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ABSTRACT

For muon-catalyzed fusion to be of practical interest, a very efficient means of producing muons must be found. We describe a scheme for producing them that may be more energy efficient than any heretofore proposed. There are, in particular, some potential advantages of creating muons from collisions of high energy tritons confined in a magnetic mirror configuration. If one could catalyze 200 fusions per muon and employ a uranium blanket that would multiply the neutron energy by a factor of 10, one might produce electricity with an overall plant efficiency (ratio of electric energy produced to nuclear energy released) approaching 30%.

One possible near term application of a muon-producing magnetic-mirror scheme would be to build a high-flux neutron source for radiation damage studies. The careful arrangement of triton orbits will result in many of the π^-'s being produced near the axis of the magnetic mirror. The pions quickly decay into muons, which are transported into a small (few-cm-diameter) reactor chamber producing approximately 1-MW/m^2 neutron flux on the chamber walls, using a laboratory accelerator and magnetic mirror. The costs of construction and operation of the triton injection accelerator probably introduces most of the uncertainty in the viability of this scheme. If a 10-μA, 600 MeV neutral triton accelertor could be built for less than $100 million and operated cheaply enough, one might well bring muon-catalyzed fusion into practical use.

I. INTRODUCTION

The EG&G Idaho/Los Alamos Meson Physics Facility (LAMPF) experiments on muon-catalyzed fusion[1,2] have revived interest in the muon catalyzed fusion process[3] as a source of fusion neutrons. Before this process could be economic, one would need an efficient and cheap way to produce μ^-'s, which is the subject of this paper. We will assume here that the fusion yield is the very likely attainable 200 fusions/μ^-. For this yield, a production rate of 5 x 10^{17} μ^-'s corresponds to a fusion power of 300 MW. This level of fusion power output would allow one to use a fast-fission (^{238}U) blanket to produce 3000 MW of nuclear power and fuel for approximately four light water reactors of 1000-MW electrical power each. As was noted by Petrov[4] the break-even Q for such an arrangement is fairly low (0.5). However, realistically, one would require Q $\geq$ 3 to make such an arrangement economically practical.[5] With a suppressed fission blanket, one would require Q $\geq$ 6.

We believe that the best way to produce μ^-'s for fusion catalysis is to employ colliding triton beams.

One may estimate π^- cross sections from the measured values for π^+ production in p-p collisions and π^- production in p-n collisions. If we neglect the shadowing effect of one nucleon on another in the triton (the "Glauber effect"), the pion production cross-section will be given entirely in terms of nucleon-nucleon cross-sections for π^- production. Taking into account the relative numbers of neutrons and protons in a triton[6] and making use of the charge symmetry[6] relation $\sigma(n + n \rightarrow n + p + \pi^-) = \sigma(p + p \rightarrow n + p + \pi^+)$ we obtain

$$\sigma(t+t\rightarrow\pi^-+\ldots) \sim 4\sigma(p+p\rightarrow n+p+\pi^+) + 4\sigma(p+n\rightarrow p+p+\pi^-) + 4\sigma(p+n\rightarrow p+n+\pi^+ +\pi^-) \quad (1)$$

as an initial estimate of the π^- production cross-section. For example, at a laboratory energy of 900 MeV/amu, corresponding to a center-of-mass energy of 200 MeV/amu, the sum of the three terms is 90 mb.[6] If we reduce this estimate by 20% to account for shadow corrections we obtain

$$\sigma(t+t\rightarrow\pi^-+\ldots) \sim 70 \text{ mb} \quad , \quad (2)$$

as an estimate for the μ^- production cross section at a center-of-mass energy E_{CM} of 200 MeV/amu.

From estimates of the total cross section for inelastic triton-triton collisions one can guess that approximately two-thirds of triton-triton collisions at a lab energy of 900 MeV/amu lead to π^-'s. If one were to produce π^-'s by directing a 900-MeV/amu tritium beam at a fixed tritium target the beam energy needed to produce a μ^- would be approximately 3/2 x 2700 MeV = 4050 MeV. Therefore, even for the production of 200 fusions (3520 MeV per μ^-) one could only hope to achieve energy break-even

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if all the triton kinetic energy were recovered. This essentially puts all the burden for economic operation of a muon-catalyzed fusion reactor on the efficiency of beam-energy recovery (e.g., in a spallation breeder).

On the other hand, using colliding triton beams to produce π^-'s with 200-MeV/amu center-of-mass energy, corresponding to a lab energy of 900 MeV/amu would require 2 x 3/2 x 600 MeV = 1800 MeV. This value is more than a factor of two smaller than the fixed-target one. In addition, the energy of the 200-MeV neutrons produced in the triton-triton collisions can be substantially multiplied in a uranium blanket. Therefore, in the case of colliding beams, the fraction of total nuclear energy released that is needed to run the accelerator is much smaller than that for fixed-target production of muons.

2. MAGNETIC MIRROR SCHEMES

Once the tritons are injected and trapped in the "magnetic bottle" they are confined either until they react or until they leak out by angular scattering. The magnetic field can be used to guide the pions to the D-T reaction chamber, where the muons having decayed from the pions will slow down and begin catalyzing fusion reactions (see Fig. 1).

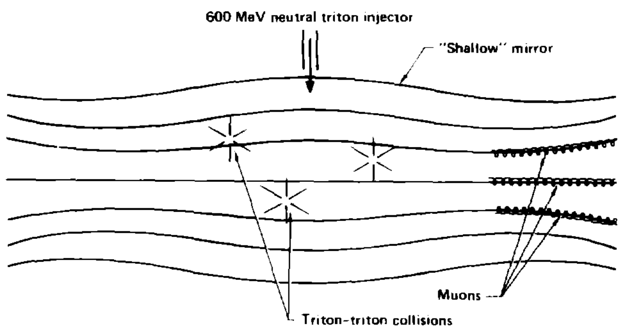

Fig. 1. Magnetic mirror configuration for confining 600 MeV tritons. Triton collisions produce muons.

The energy of the triton perpendicular to the magnetic field is denoted by $E_\perp$ and the total energy by E; r is called the mirror ratio.

$$E_\perp/E \geq 1/r \quad . \qquad (3)$$

The density of tritons that can be confined is limited by loss of equilibrium, sometimes known as the "mirror instability," which sets a limit on the confinement β, defined as the ratio $\beta \equiv nE_\perp(2\mu_0/B^2)$. For $E_\perp$ equal to 600 MeV, one has

$$n \approx 4 \times 10^{11} \beta \left(\frac{B}{10\ T}\right)^2 \ cm^{-3} \quad . \qquad (4)$$

For a realistic mirror ratio, (e.g., r = 1.1), the mirror instability limits β to values less than 1/4 (Ref. 8). For B $\leq$ 20 T we then have n $\leq$ 4 x 10^{11} cm^{-3}. Experiments have been run with β as high as 1.5 when the plasma length is of the order of the gyro-radius (Ref. 9). This high β may be achievable for the neutron source used for radiation-damage discussed below because the plasma length can be short.

The minimum radius for a reaction-chamber radius will be determined by the magnetic rigidity:

$$RB = 6.4\ T\ m. \qquad (5)$$

For example, B = 15 T corresponds to an inside diameter of 1.7 m. In general one would want to make the reaction chamber large to maximize the muon output yet sufficiently small to minimize the reaction-chamber cost.

The pion production rate in the reaction chamber will be

$$\dot{N}_{\pi^-} = \frac{\pi}{8} D^2 L\ n^2 \langle\sigma v\rangle \quad . \qquad (6)$$

where D and L are the diameter and length of the reaction chamber, $\langle\sigma v\rangle$ is the reaction rate parameter, and n is the average density of tritons. If, in accordance with Eq. (2), we set $\langle\sigma v\rangle = 10^{-15}$ cm$^3\cdot$sec^{-1} and use Eq. (4), we obtain

$$\dot{N}_{\pi^-} \approx 4 \times \left(\frac{B}{10\ T}\right)^2 \left(\frac{L}{1\ m}\right) \beta^2\ 10^{14}\ sec^{-1} \qquad (7)$$

where we have used Eq. (5) to calculate D. If this approach seems worth pursuing a better calculation of $\dot{N}_{\pi^-}$ could be made taking into account the spatial variation of the parameters.

Assuming the pions are produced isotropically, a fraction $f = 1-(1-r^{-1})^{1/2}$ will escape out the ends. Thus we obtain the following expression for the muon current

$$\dot{N}_{\mu^-} \approx 4\ f \left(\frac{B}{10\ T}\right)^2 \left(\frac{L}{1\ m}\right) \beta^2 10^{14}\ sec^{-1} \qquad (8)$$

We conclude that with small mirror-ratio values one ought to be able to produce muon currents on the order of 6 μA with a laboratory-size (i.e., L ≈ 1 m) system. As stated earlier two-thirds of the triton-triton collisions result in muons, so the production of 6 μA of muons requires about 9 μA of tritons. The efficiency of making and accelerating tritons can be as high as 50% but high energy accelerators only become efficient when fully loaded. The power to operate the accelerator is substantial even at current in the microampere range and in fact doesn't increase much until the beam current approaches the range of 0.1 amperes.

If we assume that the cumulative loss of muons associated with transporting them into the D-T reaction chamber is less than 50%, then Eq. (8) implies that one has about 2×10^{13} muons per second available for fusion catalysis. Assuming that each muon catalyzes 200 fusions, we find that a laboratory-scale system could produce about 10 kW of fusion power. Unfortunately, it does not appear that a magnetic mirror system such as we described could produce the 5×10^{17} muons per second required for a power station or a fission fuel breeder. Indeed, Eq. (8) implies that such a system would have to be more than 10 km long!

It may be possible to peak the density on axis by injecting the tritons so that they pass very near the axis [i.e., so that they have near-zero canonical angular momentum (see Fig. 2)]. Suppose all trapping occurs within 1 cm of the axis and scattering and electron drag only increase this radius to 2 cm. Call this radius r_2.

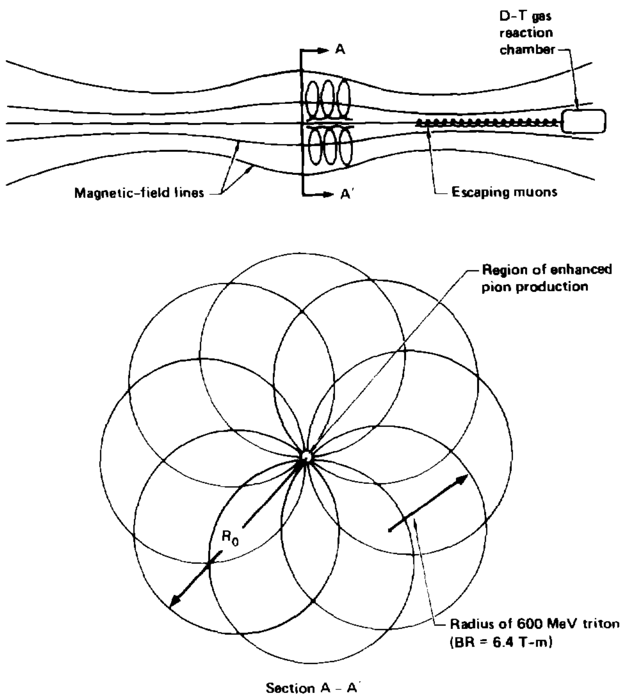

Fig. 2. Arrangement of triton orbits leading to enhanced muon production near the axis.

Further assume the β is 1 at the center. For a 10-T field the average density is 4×10^{11} cm^{-3} from Eq. (12) and the gyroradius is 64 cm from Eq. (5). The chamber radius, R_o, is then 1.28 m. One can show that the average density within r_2 is increased over that within R_o by the factor $R_o/\pi r_2$. For the values assumed above this density peaking factor becomes 10 and the reaction rate is increased by a factor of 100. The density within a 2-cm radius then is 4×10^{12} cm^{-3}. The reaction rate for a length of 50 cm is 5×10^{12} sec^{-1}. This gives a beam of muons that will provide 1 kW of D-T fusions in a small reaction chamber whose size is determined by the magnetic flux tube guiding the 2-cm-radius muons of at 10 T (e.g., 6 cm at 1 T).

Another possible approach to obtaining a higher reaction rate would be to trap a much colder but more dense triton plasma along the axis of the magnetic mirror. Such a scheme would allow one to raise the reaction rate at the expense of having to inject tritons at a higher energy and would permit one to confine a higher density plasma. In Fig. 3 we show the triton injection energy, E_b, needed to produce the Δ(3/2) resonance state as a function of target-tritons temperature, θ_T. We note that the total energy consumed per triton-triton collision is only modestly higher than the 1200 MeV required in the case of colliding 600-MeV tritons. However, the much higher injected triton-beam energy means that the capital cost of the injection accelerator would be rather high. In Fig. 4 we show the reaction-rate increase in a magnetic mirror containing a low-energy (few MeV) triton plasma into which tritons of the energy shown in Fig. 3 are injected. The actual parameter plotted is the radius, R_T,

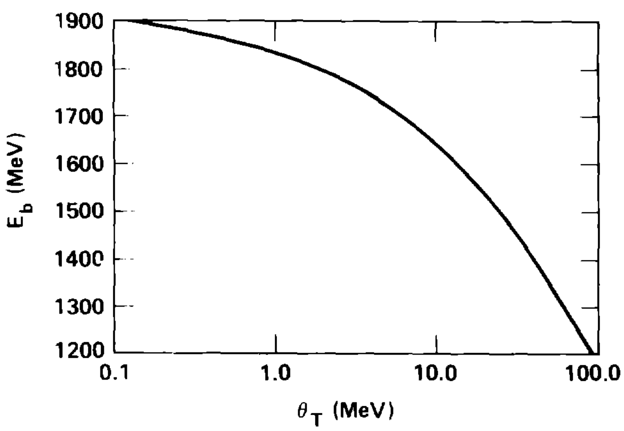

Fig. 3. Triton beam energy needed to produce the Δ resonance as a function of the temperature of a trapped triton plasma.

of a cylinder containing the low energy tritons. These tritons would give the same μ^- production as the colliding 600-MeV-triton system relative to the magnetic-mirror radius, R_o, of the colliding triton system. It can be seen that in order to decrease this radius by a factor greater than 10, the temperature of the low-energy, high-density plasma must be less than 1 MeV. Therefore, in order to obtain very large enhancements in muon production one needs to trap a triton plasma whose temperature is similar to that used in conventional magnetic fusion. Instead of a problem

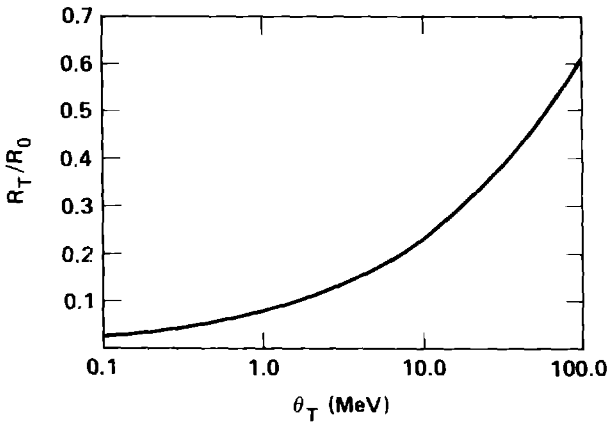

Fig. 4. Radius of trapped triton plasma required to give same μ production as trapped 600 MeV tritons. The parameter $R_0 = 2$ R where R is defined in Eq. (4).

involving colliding 600-MeV tritons at low density (10^4 cm^{-3}), one now has one problem involving stable confinement of cooler-than-1-MeV plasmas at high densities ($\sim 10^{14}$ cm^{-3}).

3. IN SITU ACCELERATION OF TRITONS BY MAGNETIC COMPRESSION

Tritons injected and trapped in the magnetic bottle can be given additional energy efficiently and cheaply by increasing the magnetic field strength (i.e., by magnetic compression). The compression ratio CR is defined as the final magnetic field strength divided by the initial magnetic field strength. A compression ratio of 100, if achievable, would reduce the 600 MeV injection energy to 6 MeV. The initial gyroradius, a_i, in terms of the final gyroradius, a_f, is $a_i = (CR)^{0.5} a_f$. For a 600-MeV triton and a final field of 15 T, $a_f = 0.4$ m. The parameter a_i is 4 m for a compression ratio of 100 and the initial field is 0.15 T. So that the bore of the coils is not too large, compression should be done in stages; that is, the tritons should be compressed then translated into a smaller-diameter coil set for further compression, and so on.

4. DISCUSSION OF ENERGETICS

The colliding beam scheme that we have described appears to be fairly promising from the point of view of energy efficiency. For example, if tritons are injected into a magnetic mirror with an energy of 600 MeV, the electrical energy used to produce one muon will be approximately

$$\text{Electrical energy used} \approx \frac{1800 \text{ MeV}}{\eta} \qquad (9)$$

where η is the efficiency of making, accelerating, and trapping the tritons. Assuming that some fraction $\tilde{f}$ of the muons produced actually makes it into the reaction chamber, and that each muon catalyzes 200 D-T fusion reactions, the energy released by each muon produced will be

$$\text{Energy produced} = 3500\ \tilde{f} \text{ Me} \qquad (10)$$

Since $\tilde{f} < 0.5$, we see that even if $\eta = 0.5$ we cannot achieve break-even with respect to the electricity used to power the injection accelerator. However, one can recover some of the energy of the protons and neutrons produced in the triton-triton collisions (e.g., by using the neutrons to produce fission energy in a uranium blanket). Comparison of Eqs. (9) and (10) shows that one would need to recover about one-half of the triton beam energy in order to achieve energy break-even.

Let us try to estimate what overall efficiency might realistically be achieved for a muon-catalyzed fusion power plant. We define Q_1 as the fusion energy released (14-MeV neutron and 3.6-MeV alpha) divided by the injected triton energy. The parameter Q_2 is defined as the neutron energy produced in the triton reaction chamber divided by the injected triton energy. The electrical efficiency, η_{el}, for the system shown schematically in Fig. 5 is defined as

$$\eta_{el} = \frac{\text{Triton energy } P\eta_{th} - \text{Triton energy}/\eta}{\text{nuclear energy released}}$$

$$= (P\eta_{th} - 1/\eta)/P$$

where $P = .8Q_1M_1 + 0.2Q_1 + Q_2M_2$, and M_1 and M_2 are the energy multiplication factors for the uranium blankets, and η_{th} is the thermal-energy-to-electricity conversion efficiency.

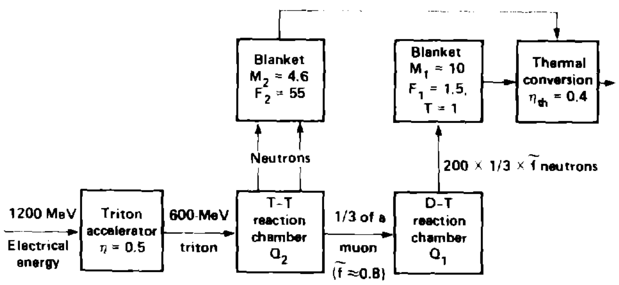

Fig. 5. Schematic of muon fusion-energy flows and breeding rates.

As discussed earlier each triton ends up producing one-third of a muon. Of these muons a fraction, $\tilde{f}$, manages to get into the D-T reaction chamber where each muon makes 200 D-T reactions. We assume $\tilde{f}$ equals 0.8, so that

$$Q_1 = \frac{\frac{1}{3} \times 0.8 \times 200 \times 17.6 \text{ MeV}}{600 \text{ MeV}} = 1.56 \ .$$

If the triton reaction chamber and blanket are as effective as conventional accelerator breeder targets, we can set Q_2M_2 equal to the energy multiplication quoted for accelerator breeder designs, $Q_2M_2 = 4.6$ (see p. 23 of Ref. 10).

We will assume a thermal conversion efficiency of 0.4 and an accelerator efficiency η of 0.5. Assuming a blanket multiplication M_1 of 10 for a depleted uranium blanket, we have

$$\eta_{el} = \frac{(12.5 + 0.3 + 4.6)\ 0.4 - 2}{17.4}$$

$$= 28.5\%$$

We see that the accelerator breeder blanket produces about as much electrical energy as is needed to power the accelerator (i.e., electrical break-even energy). The muon-catalyzed fusion reactions produce 2.8 times as much electrical energy.

The breeding will now be estimated. The value of F_2 given on p. 22 of Ref. 10 for 500-MeV deuterons is $(24 \times 1.9) = 46$, where F_2 is the number of Pu atoms produced per injected triton. For 600-MeV deuterons we expect a linear improvement with energy, so F_2 becomes 55. The arrangement in Ref. 10 consists of a lithium primary target and uranium secondary target. In our case we use an ionized energetic-triton primary target. The tritium produced in the blanket of the muon chamber just replaces that consumed. The plutonium produced is 1.5 atoms per fusion reaction. For each injected triton there are $0.8 \times 13 \times 200 = 53$ fusion reactions and 80 plutonium atoms produced. Total plutonium production is 135 atoms per injected triton. The total nuclear energy released is

$$E_{nuclear} = 600 \text{ MeV } P = 10{,}440 \text{ MeV},$$

giving 0.013 atoms per MeV for Pu production. This equals 0.9 kg/$MW_{nuclear}$ year. The analysis here is similar to that of Ref. 11. However, we get better results due in part to the higher muon production efficiency and to the fact that we assumed 200 fusions per muon where Ref. 11 assumed 100 fusions per muon.

5. CONCLUSION

The main disappointment of the magnetic mirror schemes described in Sections 2 and 3 is that, to produce the $5 \times 10^{17}\ \mu^-$/sec needed for a 300-MW fusion power plant, the size of the mirror would have to be unacceptably large unless a cold triton plasma were used as a target. This latter option sacrifices many of the advantages of colliding triton beams. We hope that a more acceptable solution to this problem will emerge in the future.

One possible near term application of a muon-producing magnetic-mirror scheme would be to build a high-flux neutron source for radiation damage studies. As described in Section 3, the careful arrangement of triton orbits can result in many of the π^-'s being produced near the axis of the magnetic mirror. The transport of the muons into a small (few-cm-diameter) reaction chamber could evidently produce approximately 1 MW/m^2 neutron fluxes with a laboratory accelerator and magnetic mirror. The cost of construction and operation of the injection accelerator probably introduces most of the uncertainty in the viability of this scheme. If a 10-μA, 600-MeV neutral triton accelerator could be built for less than $100 million and operated cheaply enough one might well bring muon-catalyzed fusion into practical use.

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